V. Shergotty

Basalt, 5 kg.
*seen to fall*

Introduction

The Shergotty achondrite fell on August 25, 1865 at 9:00 a.m. near a town called Shergahti in Bihar State, India after detonations were heard (Graham *et al.,* 1985). Duke (1968) refers to several stones with fusion crusts, *but this can not be confirmed.* The main mass is at the Museum of the Geological Survey in Calcutta, India (figure V-1). In 1984, an international consortium was organized by J. C. Laul to study ~30 grams of Shergotty in detail (Laul, 1986 a,b).

The two shergottites (Shergotty, Zagami) are texturally and mineralogically similar to terrestrial diabases (although all of the plagioclase has been shocked to maskelynite), but quite distinct petrologically and chemically from the rest of the basaltic achondrites (Stolper *et al.,* 1979). Stolper and McSween (1979) noted that Shergotty crystallized under relatively oxidizing conditions.

The Shergotty meteorite has been severely shocked and is considered the "*type locality*" for maskelynite (dense plagioclase glass). In fact, it has proven to be very difficult to date the original crystallization event of Shergotty, perhaps because of the rather severe shock history that the sample has experienced since it originally crystallized *(see El Goresy et al., 1998).*

Figure V-1. Photograph of main mass of Shergotty meteorite showing fusion crust and broken surface. Two saw cuts are visible. Sample is about 25 centimeters across. Photo kindly provided by Prof. N. Bhandari, Director, Physical Research Laboratory, Ahmedabad, India.
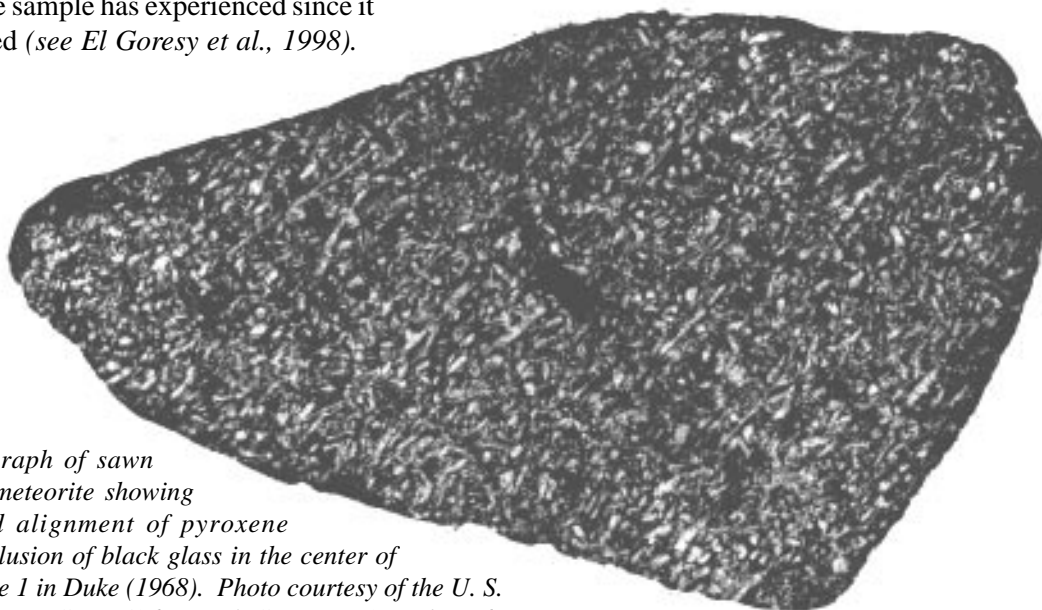
Figure V-2. Photograph of sawn surface of Shergotty meteorite showing basaltic texture and alignment of pyroxene crystals. Note the inclusion of black glass in the center of this slab. This is figure 1 in Duke (1968). Photo courtesy of the U. S. National Museum, negative # M-1426. Sample # USNM 321. About 6 cm across.

Petrography

The mineralogy and petrology of Shergotty have been comprehensively studied by many investigators (*e.g.* Tschermak, 1872; Binns, 1967; Duke, 1968; Smith and Hervig, 1979; Stolper and McSween, 1979; Nakamura *et al.,* 1982; Jagoutz and Wänke, 1986; Stöffler *et al.,* 1986; Lundberg *et al.*, 1988 and others).

Shergotty consists of dull gray-green pyroxene prisms up to 1 cm long with colorless lath-like and interstitial vitreous maskelynite which has replaced the feldspar (Duke, 1968). Shergotty exhibits a foliated texture produced by preferential orientation of pyroxene prisms and maskelynite grains (Duke, 1968; Stolper and McSween, 1979)(figure V-2). The texture was described as ophitic by Michel (1912), but the rather euhedral pyroxene does not enclose feldspar (Duke, 1968). The average grain size for Shergotty is only about 0.46 mm (figure V-3).
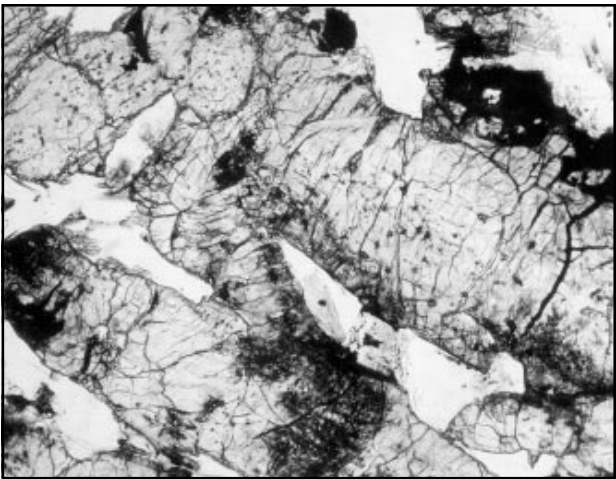

Figure V-3. Photomicrograph of thin section of Shergotty meteorite showing large clinopyroxene crystals separated by white maskelynite laths. Thin section kindly provided by Gordon McKay, JSC. Field of view is 2.2 mm.

Mineral Mode

	Stolper & McSween 1979		Duke 1968	Smith & Hervig 1979	Stöffler et al. 1986
	mode	*mode*	*norm*	*mode*	*mode*
Pyroxene	70.5	69.1	68.9	70	67
Plagioclase	23.9	22.7	24.0	20	24
Mesostasis	2.8	5.2		3	3
Magnetite	2.0	2.5	2.3	2	2
Ilmenite	0.5	0.3	1.8	0.5	0.2
Pyrrhotite	0.3	0.2	- -		0.4
Phosphate	tr	tr	1.3	1	2
silica					0.5

In thin section, pyroxene prisms vary in color from light brown in the cores to yellow brown at the rims, reflecting a marked enrichment of iron at the rims (Duke, 1968). Maskelynite is transparent, colorless, conchoidally fractured, isotropic and is a pseudomorph after plagioclase (see below). Based on the texture, plagioclase crystallized late in the sequence of crystallization (Stolper and McSween, 1979; Treiman, 1985a).

Melt inclusions in pyroxene are an important assemblage in Shergotty (Nyquist *et al.,* 1979; Treiman, 1985a). They represent trapped magmatic liquid and may allow a determination of the age of entrapment during crystallization (see below).

The coexistence of fayalite, Ti-magnetite and a silica glass indicates late-stage crystallization under relatively high oxygen fugacity (Smith and Hervig, 1979).

Shergotty should be examined for the presence of large shock-melted "*glass pockets*" similar to those found in Zagami and EETA79001 (figure V-2). In fact, Stöffler *et al.* (1986) refer to substantial amounts of "*localized in-situ melting*" confined to grain boundaries between pyroxene and opaque phases.

Mineral Chemistry

Pyroxene: Pyroxene consists of separate grains of pigeonite and sub-calcic augite, both with a homogeneous interior and a strongly zoned Fe-rich rim (figure V-4). Smith and Hervig (1979), Stöffler *et al.* (1986) and Lundberg *et al.* (1988) have studied pyroxene zoning - both major and trace elements. There are two trends, Ca-rich from $En_{48}Fs_{19}Wo_{33}$ to $En_{25}Fs_{47}Wo_{28}$, and Ca-poor from $En_{61}Fs_{26}Wo_{13}$ to $En_{21}Fs_{61}Wo_{18}$. Mn increases along with Fe (figure V-5), and Smith and Hervig and Stolper and McSween
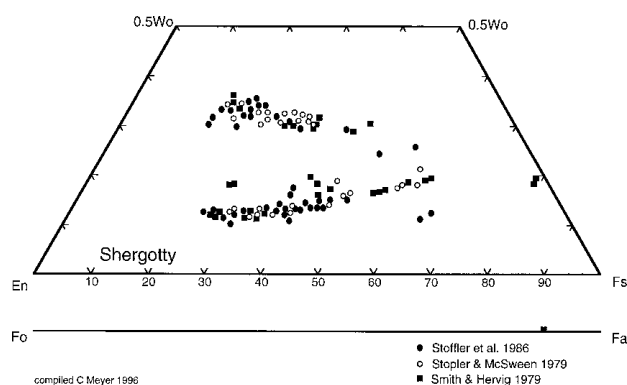
Figure V-4. *Pyroxene composition diagram for Shergotty meteorite. Data combined from several sources including Stöffler et al. (1986), Stolper and McSween (1979) and Smith and Hervig (1979).*

Figure V-5. *Variation between MnO and FeO in pyroxenes in Shergotty and Zagami meteorites. This is figure 5 of Stolper and McSween (1979), GCA* **43**, *1480.*
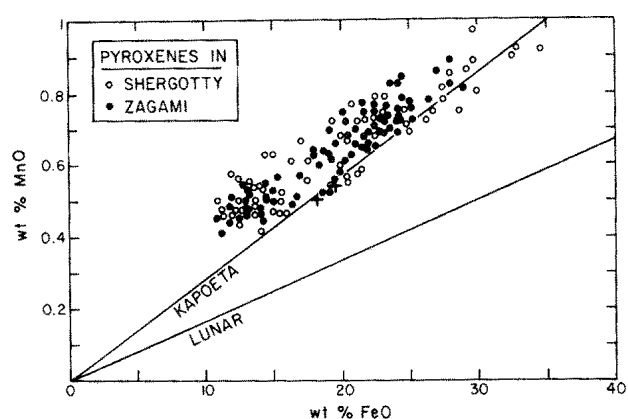
(1979), found that the trend is towards an intercept of MnO near 0.2 % for low Fe. The preservation of extreme chemical zoning in pyroxenes indicates rapid cooling. Wadhwa *et al.* (1994) studied the trace elements in pyroxenes in Shergotty (figure IX-14)

Müller (1993) studied "microstructures" in Shergotty clinopyroxene. Fine scale exsolution also argues for rapid crystallization in a lava flow or sill about 40-60 meters thick.

Pyroxferroite: Smith and Hervig (1979) reported minute grains of pyroxferroite included in maskelynite.

Maskelynite: Shergotty is the type specimen for maskelynite (Tschermak, 1872), a plagioclase glass formed by high shock pressures estimated at ~300 Kbars (Smith and Hervig, 1979) or 29 Gpa (Stöffler *et al.,* 1986). Binns (1967) found that the maskelynite in Shergotty lacks any crystal structure, as evidenced by isotropism and absence of diffraction lines in long-exposure X-ray powder photographs. Duke (1968) noted that the refractive indices and specific gravities of maskelynite grains are variable, and suggested that individual crystals are zoned. Easton and Elliot (1977) reported the composition of "feldspar/glass" from Shergotty as $An_{51.2}Ab_{46.5}Or_{2.3}$. Stolper *et al.* (1979) determined that individual maskelynite grains are zoned from $An_{57}Ab_{42}Or_1$ to $An_{43}Ab_{53}Or_4$.

K-rich inclusions: The pyroxenes in Shergotty contain K (and Rb) rich inclusions (Nyquist *et al.,* 1979). It is these inclusions that apparently define the Rb/Sr isochron.

Phosphates: Most of the trace elements in the rock are in the phosphates. Fuchs (1969) gave an analysis of whitlockite in Shergotty. Jagoutz and Wänke (1986) give the composition of apatite and whitlockite. Smith and Hervig (1979) reported merrillite (?) in glass veins. Lundberg *et al.* (1988) analyzed both whitlockite and apatite for REE by ion microprobe. Wadhwa *et al.* (1994) compare whitlockites in the shergottites. In 1996, Dreibus and Wänke performed detailed leaching experiments on the phosphates.

Magnetite: Tschermak (1872) was the first to recognize primary magnetite in Shergotty. This important observation, overlooked for many years, indicates a relatively high degree of oxidation at the time of crystallization.

Baddeleyite: Smith and Hervig (1979) reported rare, small (~1 micron) grains of baddeleyite. Lundberg *et al.* (1988) found that baddeleyite had a flat REE pattern.

Hercynite spinel: Treiman (1985) reported Fe, Al-rich spinel in magmatic inclusions in pyroxene.

Amphibole: Treiman (1984, 1985) reported pleochroic amphibole in the magmatic inclusions in pyroxene. Amphibole has been analyzed for D/H ratio by Watson *et al.* (1994).

Sulfide: The sulfide in Shergotty was recognized to be pyrrhotite by Tschermak (1872). Smith and Hervig (1979) describe it as "homogeneous with molar Fe:S of 0.94, and 0.12 wt % Ni, 0.03 Cu." It is found in the rims of the pyroxene and in the mesostasis.

Silica: Duke (1968) reported silica (cristobalite ?), but could not find x-ray lines for coesite. Stöffler *et al*. (1986) reported a large grain (~200 microns) of α-quartz adjacent to maskelynite and one grain of possible stishovite (?). El Goresy *et al*. (1996, 1997, 1998) and Sharp *et al*. (1998) found that *"silica grains in Shergotty consist of two phases: (i) a dense amorphous silica glass, and (ii) a post-stishovite polymorph of SiO$_2$". (see section on Shock Effects)*

Fayalite: Smith and Hervig (1979) found that fayalite (Fo$_{10}$) was present in the mesostasis adjacent to magnetite-ilmenite grains.

Whole-rock Composition

The major element composition of Shergotty was determined by Tschermak (1872), Duke (1968), McCarthy *et al.* (1974), and Dreibus *et al.* (1982). The Shergotty Consortium (Laul *et al.,* 1986) obtained additional chemical data on Shergotty (table V-1). The REE data are compared in figure V-6. Laul *et al.* (1986) noted a slight difference in the REE abundance from fragments B and C from opposite sides of the main mass, possibly indicating some heterogeneity in the sample.

In addition to the data table, Allen and Clark (1977) determined 58 ppm F and reported 56.2 ppm F by Reed and Jovanovic (1969). Gibson and Moore (1983) and Gibson *et al.* (1985) reported two values for S in Shergotty (360 and 2170 ppm respectively). Dreibus *et al.* (1983) and Laul *et al.* (1986) reported 1330 and 1579 ppm S. Burgess *et al.* (1989) found 1930 ppm S and suggested that the wide range of reported values is due to sample heterogeneity (see figure II-7). Dreibus and Wänke (1987) reported 36 ppb I, 890 ppb Br, and 108 ppm Cl. Jovanovic and Reed (1987) reported 470 ppb Hg *(probably Museum contamination).*

Yang and Epstein (1985) reported 180 ppm H$_2$O in Shergotty. Karlsson *et al.* (1992) reported 640 ppm H$_2$O, but recognized that some of this may be terrestrial *(see section on Other Isotopes).* Gooding *et al*. (1990) determined the thermal release pattern for several volatile species.

Stolper (1979) noted the remarkable similarity of Shergotty and Zagami with terrestrial basalts for a wide range of elements (figure V-7). However, Dreibus *et al.* (1992) noted that Shergotty had much
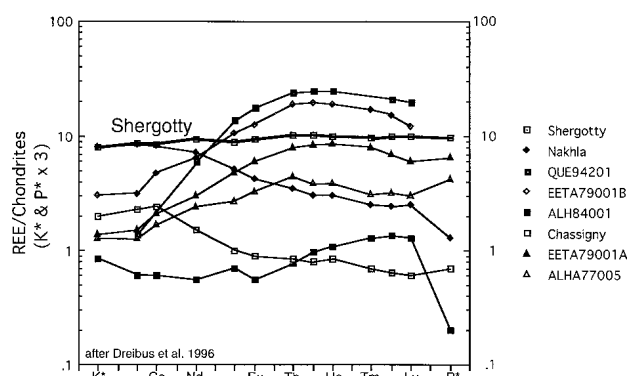
Figure V-6. REE diagram comparing Shergotty with other Martian meteorites. This diagram is redrafted from Dreibus et al. (1996).
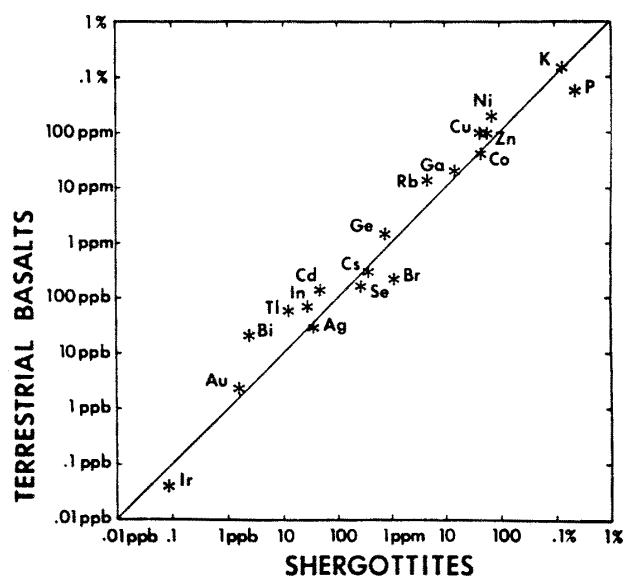
*Figure V-7. Comparison of the composition of Shergotty with average composition of terrestrial basalts by Stolper (1979), EPSL **42**, 239.*

less Ir than the other Martian meteorites and/or terrestrial "upper mantle."

Note: The values for the composition of Shergotty reported by Schmitt et al. (1972) are so far off that Smith and Steele (1979) asked if they analyzed the wrong sample!! Also the values given for Shergotty in the book on Basaltic Volcanism (Lofgren and others, 1981) do not seem to be consistent with literature values.

Radiogenic Isotopes
The original crystallization age of Shergotty has proven to be most difficult to determine. Geiss and Hess (1958) originally determined a K/Ar age of 560 Ma

Table V-1. Chemical composition of Shergotty.

	Treiman 86	Dreibus 82	McCarthy 74	Jerome 70	Philpotts70	Tscher. 1872	Duke 1968	Smith 84	Shih 82	Ma 81	Warren 87
weight	*0.1-0.2 g*		*1 g*	*1.065 g*						*(Irving)*	
SiO2 %		51.36	50.36 (f)	51.48 (a)		50.21 (e)	50.1 (e)				
TiO2		0.87		0.81 (a)			0.92 (e)				
Al2O3		7.06	7.03 (f)	5.75 (a)		5.9 (e)	6.68 (e)				6.42
Fe2O3							1.49 (e)				
FeO		19.41	19.34 (f)	19.8 (a)		21.85 (e)	18.66 (e)				18.93
MnO		0.52	0.54 (f)	0.49 (a)			0.5 (e)				0.515
CaO		10	9.58 (f)	10.25 (a)		10.41 (e)	10.03 (e)				8.81
MgO		9.28	9.27 (f)	9.35 (a)		10 (e)	9.4 (e)				9.78
Na2O		1.29	n.d.	1.31 (a)		1.28 (e)	1.28 (e)				1.34
K2O		0.164	0.18 (f)	0.13 (a)	0.18 (d)	0.51 (e)	0.16 (e)				0.178
P2O3		0.8	0.47 (f)				0.71 (e)				
sum		**100.754**	**97.62**	**99.37**		**100.16**	**99.93**				
Li ppm		5.6							4.1 (d)		
C		620									
F		41.6									
S		1330									
Cl		108			**Jerome 70**						
Sc		58.9		48 (b)	50.3 (c)		72 (b)	52		53 (c)	53
V				380 (b)			340 (b)				290
Cr		1389	2100 (f)	1500 (b)	1400 (c)	**Laul 72**	1150 (b)				1330
Co		39		37 (b)	39.5 (c)	63 (g)	42 (b)	38 (g)		35 (c)	39
Ni	55 (g)	83		81 (b)			100 (b)	56		56 (c)	80
Cu		26		11 (b)		11.9 (g)		54			
Zn	68.3 (g)	83				76 (g)		76 (g)			54
Ga		14.7				13.9 (g)		15 (g)			16.7
Ge	0.69 (g)										
As		0.025						6.03 (g)			
Se	0.37 (g)	0.41				0.242 (g)		0.47 (g)			
Br	1.06 (g)	0.891 (j)				1.07 (g)					
Rb	9.5 (g)	6.84			0.13 (d)	6.1 (g)		5.7	6.22 (d)		
Sr		51		35 (b)	50.7 (d)		8 (b)		51 (d)		
Y				<10 (b)			19 (b)				
Zr							41 (b)				
Nb							22 (b)				
Mo											
Pd ppb	1.7 (g)										
Ag ppb	16.9 (g)					263 (g)		110 (g)			
Cd ppb	12.9 (g)					44 (g)		340 (g)			
In ppb	26.5 (g)					31.3 (g)		23 (g)			
Sb ppb	1.7 (g)	<5						27 (g)			
Te ppb	2.5 (g)							3.2 (g)			
I ppm		0.036 (j)									
Cs ppm	0.529 (g)	0.405			**Schnetz. 69**	0.38 (g)		0.44 (g)			
Ba		35.5		40 (b)	32 (d)		6 (b)		29.4 (d)		
La		2.29		1.93 (c)					1.5 (d)	2.18 (c)	1.99
Ce		5.54			5.89 (d)				3.51 (d)		
Pr		0.86									
Nd		4.5			4.96 (d)				2.6 (d)		
Sm		1.37		1.37 (c)	1.89 (d)				1.01 (d)	1.36 (c)	1.27
Eu		0.564		0.55 (c)	0.643 (d)				0.43 (d)	0.53 (c)	0.56
Gd		2.2			2.8 (d)				1.64 (d)		
Tb		0.44								0.36 (c)	
Dy		2.94			3.38 (d)				2.16 (d)		
Ho		0.56									
Er		1.87			1.89 (d)				1.33 (d)		
Tm		0.38									
Yb		1.69		1.4 (c)	1.8 (d)				1.19 (d)	1.59 (c)	1.48
Lu		0.25		0.34 (c)					0.176 (d)	0.262 (c)	0.23
Hf		1.97		2.15 (c)				2		2 (c)	
Ta		0.25						0.27		0.27 (c)	
W ppb		480									
Re ppb	0.044 (g)										
Os ppb	<.0023 (g)										
Ir ppb	0.0285 (g)	0.4 (k)				1.55 (g)					0.07
Au ppb	5 (g)	16				88 (g)		12 (g)			0.97
Tl ppb	12.9 (g)	12 (l)				13.4 (g)		11 (g)			
Bi ppb	0.7 (g)	2 (l)	**Morgan 73**	**Chen 86**	**Chen 86**	3.7 (g)		1.6 (g)			
Th ppm		0.39	0.465 (e)	0.439 (d)	0.398 (d)					0.35 (c)	
U ppm	0.129 (g)	0.116	0.112 (e)	0.12 (d)	0.099 (d)			0.171 (g)			

technique   (a) semi-micro wet chem., (b) emission spec., (c) INAA, (d) isotope dilution mass spec., (e) wet chem., (f) XRF, (g) RNAA

(h) INAA of less than 44 micron fraction, (i) mistake(?) see note in text, (j) Dreibus et al 1985, (k) Burghele 1983, (l) from McSween 1985, (m) elec. probe, fused sample

Table V-1. Composition of Shergotty (Continued)

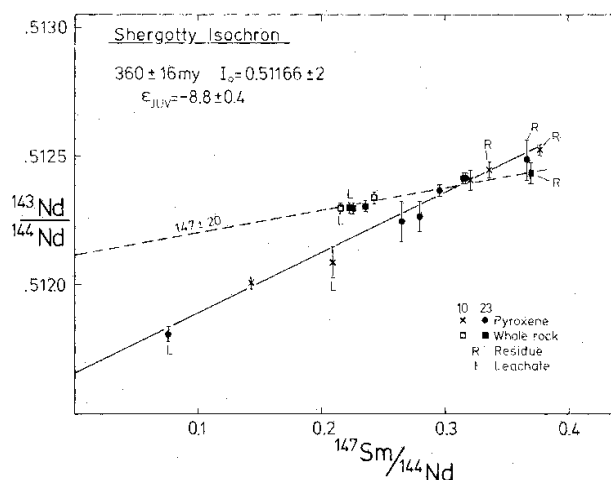|	Schmitt 72	Schmitt 72	Schmitt 72	Laul 86	Laul 86	Laul 86	Laul 86	Laul 86	Laul 86	Stolper 79	Jagoutz86	Jagoutz86
weight	*47 mg*		*915 mg 1.457 g*	*72 mg*		*90 mg*	*139.8 mg*	*130.7 mg*	*94 mg*	*240 mg*		
SiO2 %	(i)	(i)	(i)			49.5 (f)				50.4 (m)		
TiO2				0.8 (c)	0.7 (c)	0.87 (f)				0.81 (m)		
Al2O3				7.14 (c)	6.8 (c)	7.59 (f)				6.89 (m)		
Fe2O3												
FeO	16.21 (c)	14.15 (c)		19.6 (c)	19.9 (c)	19.8 (c)	20.1 (c)			19.1 (m)		
MnO	0.53 (c)	0.2 (c)		0.52 (c)	0.535 (c)	0.518 (c)	0.54 (c)			0.5 (m)		
CaO				9.52 (c)	9.72 (c)	9.63 (f)	9.88 (c)			10.1 (m)		
MgO				9.5 (c)	9 (c)	8.95 (f)				9.27 (m)		
Na2O	1.71 (c)	1.81 (c)	1.25 (c)	1.4 (c)	1.3 (c)	1.47 (c)	1.28 (c)			1.37 (m)		
K2O				0.19 (c)	0.15 (c)	0.189 (c)	0.165 (c)			0.16 (m)		
P2O3						0.72 (f)						
sum						**98.52**				**98.6**		
Li ppm						3.3 (c)						
C						430						
F												
S						1570						
Cl						108 (c)						
Sc	49 (c)	35 (c)	26 (c)	54 (c)	56.5 (c)	53.8 (c)	57.8 (c)					
V				260 (c)	265 (c)							
Cr		350 (c)		2616 (c)	2821 (c)	2923 (c)	2675 (c)					
Co	1150 (c)	62 (c)	960 (c)	37.5 (c)	38.5 (c)	37.9 (c)	39.5 (c)	37.2 (g)	37.2 (g)			
Ni				70 (c)	70 (c)	81 (c)	88 (c)					
Cu		139 (c)				26 (c)						
Zn				67 (c)	68 (c)			69.8 (g)	68.4 (g)			
Ga						17.6 (c)	16.5 (c)	17.5 (g)	15.7 (g)			
Ge												
As						0.025 (c)						
Se								0.38 (g)	0.4 (g)			
Br						0.89 (c)	0.8 (c)					
Rb								7.27 (g)	6.11 (g)		6.61 (d)	7.53 (d)
Sr				54 (c)	45 (c)						60.12 (d)	50.21 (d)
Y												
Zr				67 (c)	50 (c)							
Nb												
Mo						0.37 (c)						
Pd ppb												
Ag ppb								10.5 (g)	6.8 (g)			
Cd ppb								44 (g)	14 (g)			
In ppb								25 (g)	23 (g)			
Sb ppb								<20 (g)	8.9 (g)			
Te ppb								19 (g)	4.3 (g)			
I ppm						0.036 (c)						
Cs ppm						0.48 (c)	0.42 (c)	0.46 (g)	0.4 (g)		0.53 (d)	0.56 (d)
Ba				32 (c)	27 (c)	40 (c)	39 (c)					
La				2.44 (c)	1.95 (c)	2.44 (c)	1.97 (c)					
Ce				5.8 (c)	4.7 (c)	6.4 (c)	5.6 (c)					
Pr				0.88 (c)	0.7 (c)							
Nd				4.2 (c)	3.3 (c)	4.7 (c)	4.3 (c)				4.18 (d)	3.45 (d)
Sm				1.6 (c)	1.3 (c)	1.66 (c)	1.46 (c)				1.63 (d)	1.4 (d)
Eu				0.65 (c)	0.55 (c)	0.65 (c)	0.55 (c)					
Gd				2.6 (c)	2.1 (c)	2.8 (c)	2.5 (c)					
Tb				0.52 (c)	0.41 (c)	0.52 (c)	0.42 (c)					
Dy				3.7 (c)	3 (c)	4.8 (c)	3.1 (c)					
Ho				0.73 (c)	0.6 (c)	0.86 (c)	0.8 (c)					
Er												
Tm				0.3 (c)	0.25 (c)	0.31 (c)	0.3 (c)					
Yb				1.8 (c)	1.5 (c)	1.79 (c)	1.62 (c)					
Lu				0.26 (c)	0.22 (c)	0.26 (c)	0.24 (c)				**Lee & Halliday 97**	
Hf				2.15 (c)	1.5 (c)	2.23 (c)	1.83 (c)				1.856 (d)	
Ta				0.29 (c)	0.18 (c)	0.27 (c)	0.23 (c)					
W ppb						500 (c)	400 (c)				380.4 (d)	
Re ppb												
Os ppb												
Ir ppb				<5 (c)	<5 (c)	<3 (c)	<3 (c)					
Au ppb				<6 (c)	<6 (c)	0.9 (c)	6 (c)	5.4 (g)	0.81 (g)			
Tl ppb								14 (g)	0.15 (g)			
Bi ppb								1.2 (g)	0.47 (g)			
Th ppm				0.37 (c)	0.25 (c)	0.37 (c)	0.29 (c)					
U ppm				0.095 (c)	0.095 (c)	0.095 (c)	0.095 (c)	0.13 (g)	0.055 (g)			
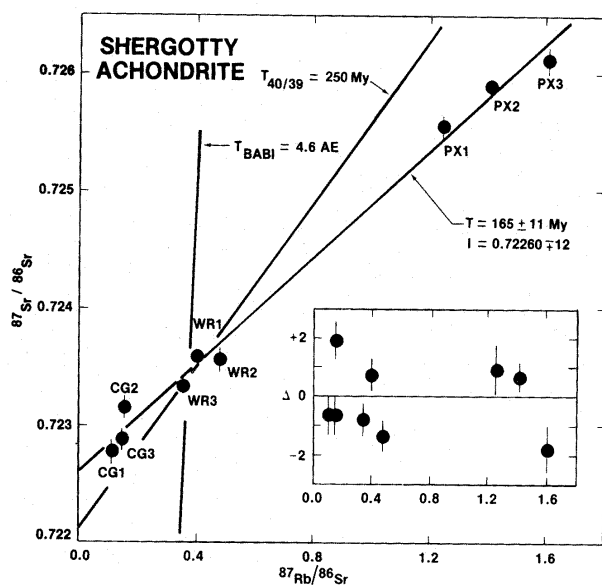
Figure V-8. *Rb-Sr isochron diagram for mineral separates and whole rock samples from Shergotty meteorite. This is figure 1 in Nyquist et al. (1979), GCA **43**, 1059.*
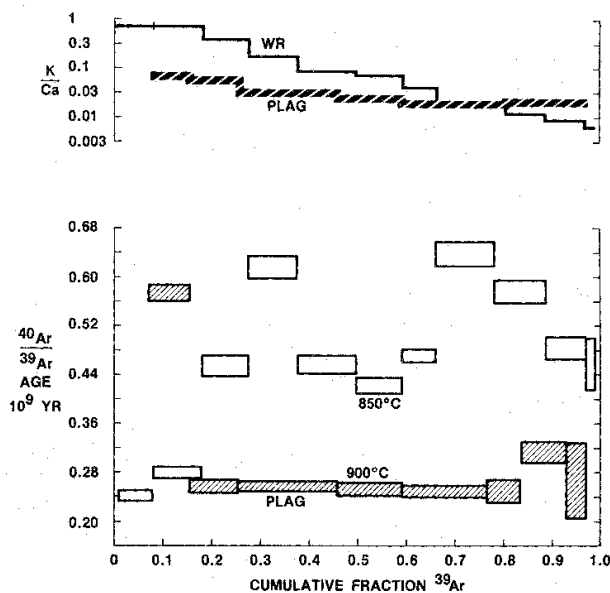
Figure V-9. *Ar plateau diagram for the age of Shergotty meteorite. This is figure 1 in Bogard et al. (1979), GCA **43**, 1049.*


Figure V-10. *Sm-Nd isochron diagram for pyroxene separates and their leachates from Shergotty meteorite. This is figure 6 in Jagoutz and Wänke (1986), GCA **50**, 946.*

(+60-150), and suggested that the Rb/Sr technique be used (page 233). Twenty one years later, Nyquist *et al.* (1979) *finally* determined an internal Rb/Sr isochron for Shergotty of 165 ± 11 Ma with high $^{87}Sr/^{86}Sr$ = 0.72260 ± 0.00012 (figure V-8) (λ_{Rb} = 1.39 x 10^{-11} year $^{-1}$). However, Bogard *et al.* (1979) attempted to determine the $^{39}Ar/^{40}Ar$ age and found that the maskelynite gave a plateau age of 254 ± 10 Ma (figure V-9). Bogard and Garrison (1998) have carefully re-

corrected the Ar data and calculate an age of 165 Ma (*should we let them get by with this?*).

Jagoutz and Wänke (1986) repeated the work of Nyquist *et al.* and reported a Rb/Sr age of 167 Ma using maskelynite and mesostasis with high I$^{87}Sr/^{86}Sr$ = 0.72263 ± 0.00005. They also reported two Sm-Nd ages (147 ± 20 Ma for leaches of the "whole rock" and 360 ± 16 Ma for the pyroxene separates and leaches)(figure V-10). Shih *et al.* (1982) were unable to use the Sm-Nd system to determine a precise crystallization age for Shergotty.

By leaching "whole rock" samples of Shergotty, Chen and Wasserburg (1986a) obtained a U-Pb "isochron" of 200 ± 4 Ma (figure V-11) and a Th-Pb "isochron" of 205 ± 8 Ma (figure V-12). These leach experiments probably attacked the phosphates in the sample (*see section on Experiments below*). By leaching the more refractory "pyroxene" separates, Chen and Wasserburg obtained "ages" 600 ± 20 Ma for U-Pb and 437 ± 36 Ma for Th-Pb.

There are many more interpretations of the age data for Shergotty than can be summarized here (*see Jones (1986, 1989) for an interesting approach*). Note that by careful petrography, Müller (1993) concluded that *"the event around 160 Ma is not responsible for the shock metamorphism displayed by Shergotty, but may be the crystallization age."*
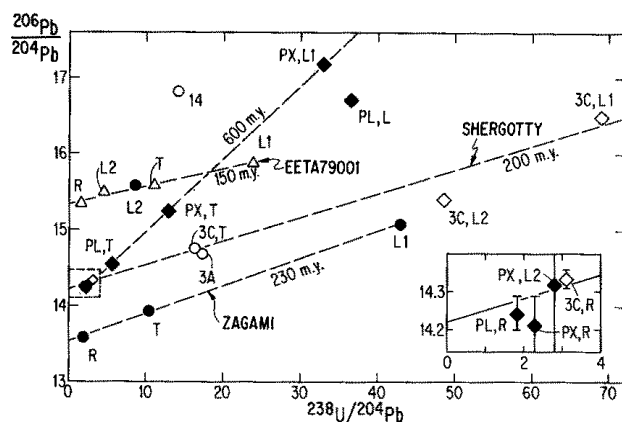
Figure V-11. *U-Pb isochron diagram for Shergotty meteorite from Chen and Wasserburg (1986c), GCA **50**, 959.*
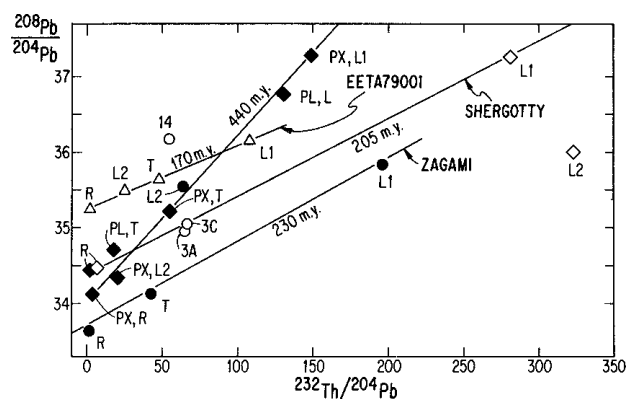
Figure V-12. *U-Th-Pb diagram for Shergotty meteorite from Chen and Wasserburg (1986c), GCA **50**, 959.*

Cosmogenic Isotopes and Exposure Ages

Heymann *et al.* (1968) reported an exposure age of ~2 Ma and Bogard *et al.* (1984b) calculated an exposure age of ~2.6 Ma for Shergotty. Nishiizumi *et al.* (1986b) reported an exposure age of 2.2 Ma. Pal *et al.* (1986) determined an exposure age of 2.7 ± 0.9 Ma using ^{10}Be. From cosmic-ray produced ^{3}He, ^{21}Ne and ^{38}Ar, Eugster *et al.* (1996) calculated an exposure age for Shergotty of 2.8 Ma (2.5 Ma using ^{3}He only) and concluded that Shergotty was *"ejected from Mars simultaneously with the other basaltic shergottites QUE94201 and Zagami"* about 2.6 Ma ago.

Other Isotopes

Taylor *et al.* (1965) found that the oxygen isotopes $^{18}O/^{16}O$ in Shergotty were different from howardites and eucrites. Clayton and Mayeda (1983, 1996) reported the oxygen isotopes for Shergotty and revised the data of Clayton *et al.* (1976). Clayton and Mayeda (1986) reported additional analyses, including mineral separates. Clayton (1993) reports the $^{18}O/^{16}O$

composition of plagioclase and pyroxene from Shergotty and calculated the equilibrium temperature.

Watson *et al.* (1994) reported the deuterium contents of hydrous amphiboles in Shergotty. Leshin *et al.* (1996) found water released from Shergotty had high D/H ratios (figure V-13).

Fallick *et al.* (1983) reported $\delta^{15}N$ as low as -40 ‰ for some steps of combustion. However, Becker and Pepin (1986) found that nitrogen was within a few per mil of terrestrial when effects of contamination and spallation are considered. Molini-Velsko *et al.* (1986) reported the isotopic composition of Si and found it normal.

Chen and Wasserburg (1986) reported the Pb isotopes in Shergotty and concluded that the parent body (Mars) was enriched in ^{204}Pb and other volatiles.

Lugmair *et al.* (1996) studied the ^{53}Mn -^{53}Cr systematics in a bulk sample of Shergotty and found that it gave the same $^{53}Cr/^{52}Cr$ excess of 0.23 ± 0.10ε as similar data from ALH84001 (figure V-14). Harper *et al.* (1995) and Lee and Halliday (1997) reported ε_{Nd} and ε_{W} that are nearly chondritic for both shergottites (figure V-19).

Bogard and Garrison (1998) have found that the black glass inclusion *(illustrated in the center of the slab, figure V-2)* contains Martian atmosphere, *somewhat different from the measurements reported by Viking.*

Experiments

Dreibus and Wänke (1996) have reported interesting experiments on the leaching of Shergotty with various solutions, showing that the phosphates readily dissolve, releasing many trace elements to the leach (*see section on Radiogenic Isotopes above*). This important experiment is applicable to what may have occurred on the surface of Mars, and may explain discordance in radiometric age determinations.

Stolper and McSween (1979) experimentally determined the phase equilibria and crystallization sequence for shergottites.

Thellier's method of paleointensity determination was applied to Shergotty (Cisowski, 1986), but the result was inconclusive, probably because of the high degree of shock suffered by Shergotty.
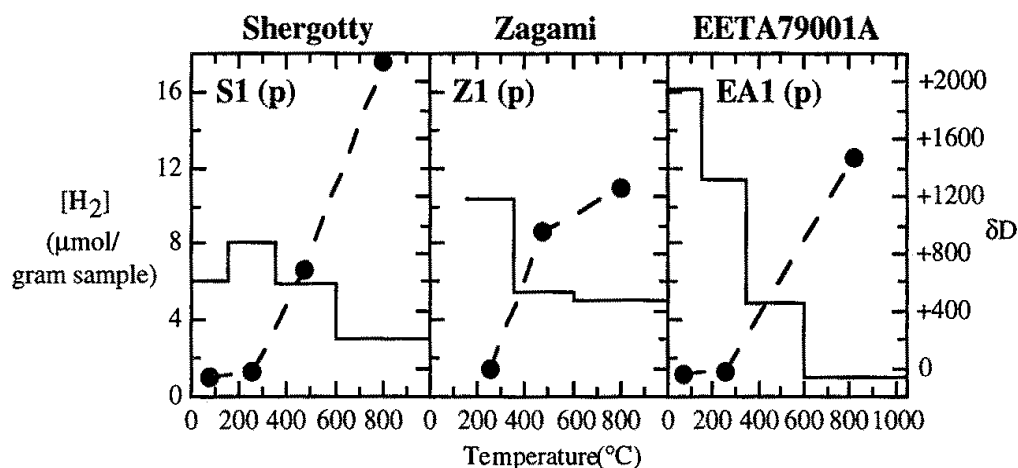
Figure V-13. *Hydrogen isotope composition of water released from Shergotty, Zagami and EETA79001 meteorites. This is a copy of figure 3 in Leshin et al. (1996), GCA **60**, 2641.*
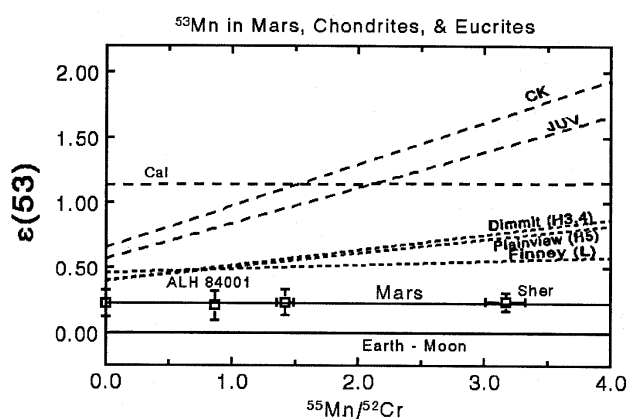

Figure V-14. *Isotopic composition of Cr for Earth, Moon, Martian and other classes of meteorites including Shergotty. This is a copy of a figure in Lugmair et al. (1996), LPS XXVII page 786.*

Fission-track mapping by Lundberg *et al.* (1988) found that only ~20 % of the U was located in the phosphates.

Bunch and Cohen (1968), Sippel (1971) and Sears and Hasan (1985) have studied the thermoluminescence of maskelynite (figure V-15).
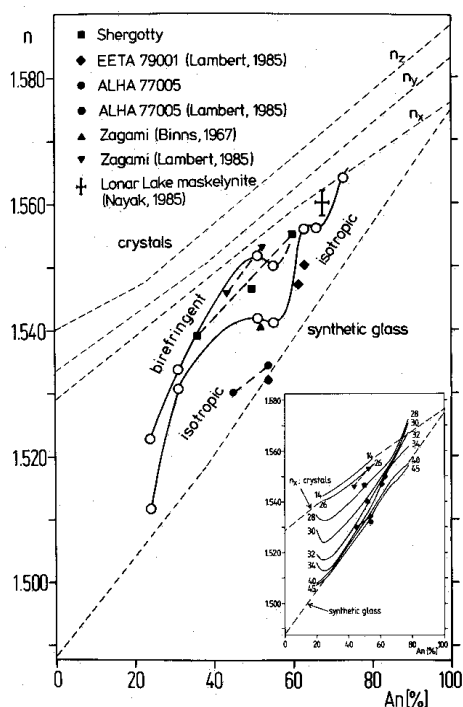
Shock Effects
The shock history of Shergotty has been much discussed. Duke (1968) concluded that Shergotty could not have been heated above 400°C following the shock. Lambert and Grieve (1984) and Gibbons and Ahrens (1977) concluded that the high index of refraction of maskelynite in Shergotty was the result of two shock events, one that originally produced the maskelynite and a second lower pressure shock thought responsible for the index of refraction. However, Stöffler *et al.*
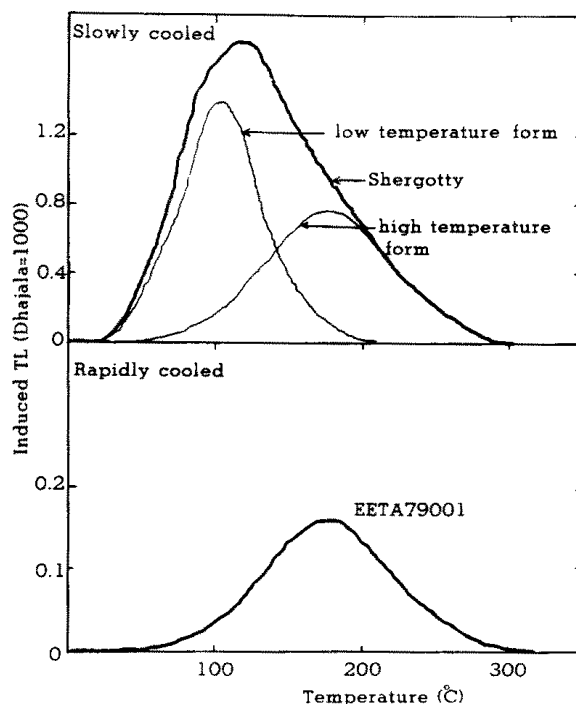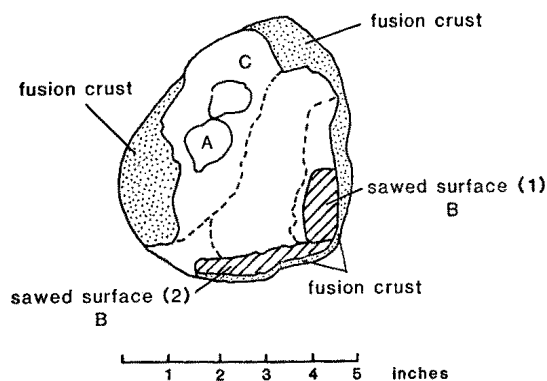

Figure V-15. *Experimental thermoluminescence glow curves for Shergotty and EETA79001 meteorites. This is figure 7 from Hasan et al. (1985), GCA **50**, 1037.*

(1986) concluded that only one shock is needed and estimated the shock pressure was 29 ± 1 GPa with a post shock temperature of 200 ± 20°C (figure V-16). Müller (1993) concluded that the magnitude of the shock event was not sufficient to reset the Rb-Sr age. Hörz *et al.* (1986) found that Shergotty pyroxenes showed continuous diffraction rings, line broadening and other evidence of substantial lattice disorder. Stöffler *et al.* reported one grain of silica that might have been stishovite (?). However, recent studies by El Goresy *et al.* (1996, 1997, 1998) are causing a

Figure V-17. Sketch of main mass of Shergotty showing the location of samples studied by Shergotty Consortium. This is figure 5 in Laul (1986), GCA **50**, 878.

Figure V-16. Refractive index measurements on plagioclase that has been shocked experimentally compared to Martian meteorites. This is figure 12 from Stöffler et al. (1986), GCA **50**, 897.
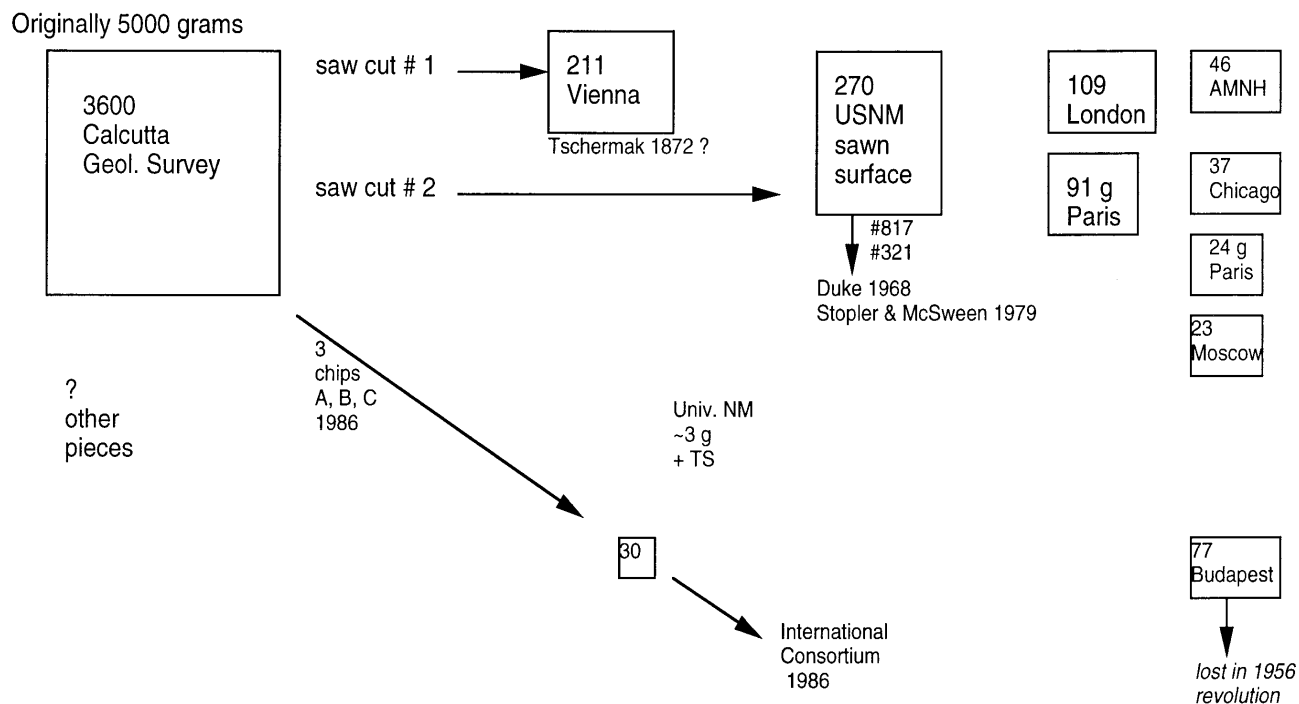
Figure V-18. Distribution of pieces of Shergotty meteorite (preliminary diagram). Was there more than one piece originally? Which research has been done on which piece?

revision in thinking about the shock effects recorded in Shergotty. Based on relic microstructures in silica grains which indicate high pressure polymorphs of silica, El Goresy *et al.* (1998) and Sharp *et al.* (1998) conclude that the peak shock pressure of Shergotty was as high as 90 Gpa.

> *Compilers Note: How can this be reconciled with the rest of the rock?*

Processing

The main mass of Shergotty (~3.6 kg.) is curated by the Geological Survey of India, in Calcutta. About 60 % of the surface of this large piece is covered with fusion crust (figure V-1). Over the years, there have been two saw cuts and several large pieces broken off. Duke (1968) refers to more than one piece of Shergotty.

In 1986, J. C. Laul and his colleagues reported the results of the international consortium study on Shergotty in *Geochimica et. Cosmochimica Acta,* vol. 50. The samples for the Shergotty Consortium (~30 g) were processed in the curatorial labs at JSC from three chips (labeled A, B and C) provided by the Geological Survey of India. Fragment A (5 g) and fragment C (13 g) were chipped from the main mass next to each other, while fragment B (12 g) was obtained from one of the areas sawn off the other side of the main mass. Figure V-17 shows the location of three chips from the main mass. Powdered samples were prepared from chips B and C for chemical analysis by the consortium (Laul *et al.,* 1986). Figure V-18 attempts to show the recent history of the various pieces of the sample.

The large black glass inclusion illustrated in the slab (figure V-2) went from the Smithsonian to Gibson to Bogard. It was found to contain the same rare gasses in the Martian atmosphere as originally found in EETA79001,27, *and in fact somewhat different from the measurements reported by Viking*
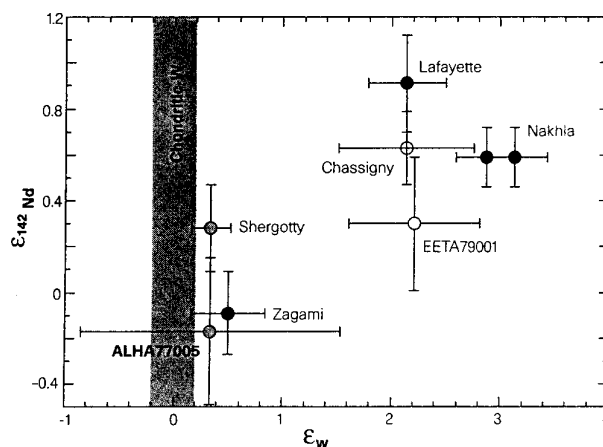
Figure V-19. *Isotopic anomalies of Nd and W for Martian meteorites (from Lee and Halliday, 1997, figure 3 in Nature 388, 856).*